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British Imbalance Market Paradox: Variable Renewable Energy Penetration in Energy Markets

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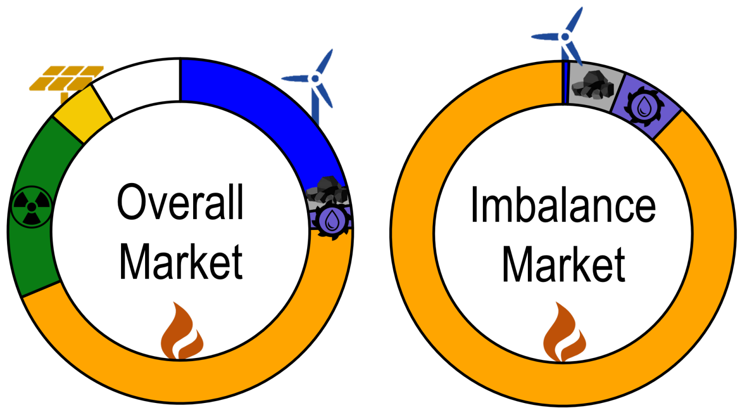
Abstract

The expansion of variable renewable energy (VRE) generation propagates numerous challenges for national energy systems. Despite recent years of VRE expansion and declining coal utilisation in the overall market profile, coal energy generation has maintained and grown its position as a marginal seller in the imbalance market. A comparative breakdown of Britain's overall market with that of Germany, followed by a specific investigation of Britain's imbalance market provides insight into changing roles of VRE, fossil fuelled energy, and compensation technologies. Historically, VRE trends in the British and German markets have been broadly consistent. Recently, increasing distress in Britain's overall market is found to result in the increased use of high pollution technologies to meet imbalances. As a result, the composition of the overall and imbalance markets have increasingly diverged, and although the dominance of gas in the latter is expected, the resurgence of coal energy is more remarkable. Thus, while the proportion of generation by renewables has continued to increase, fossil fuelled (notably including coal) capacity, and its associated infrastructure costs and influence as the price setting marginal seller, remains dominant in the imbalance market.



Highlights

- Review of VRE market trends and 'paradoxes'.
- Breakdown of VRE penetration in the markets in Germany and Britain.
- Gas dominance in the British imbalance market.
- Coal re-emergence as a marginal seller.
- Recommendations for techno-economic and storage modelling.

Contents

1 Introduction

Over the past decade, the expansion of renewable energy generation has served as a core environmental strategy in Germany and the UK. In these countries, variable renewable energy (VRE) generation infrastructure such as photovoltaic (PV) solar, and primarily wind power have been expanded in an effort displace fossil fuel energy (primarily coal, as well as gas) [62]. As VRE life-cycle and electricity production emissions rates are comparably lower than fossil fuel generation, successful integration of VRE sources is crucial to the energy transition [70, 74]. Understanding the effects of this transition is of particular interest to countries such as these with high and increasing levels of VRE penetration [34, 35, 92].

The energy transition has been studied from a variety of focal viewpoints. Differing cost structures (and market effects) [40, 49], supply chain complexities and circular economy applications [54], construction times, geographic constraints [37, 64, 99, 100], storage and compensation requirements [44, 57, 58, 84], micro-grid potential [95], seasonality [17, 21], and grid effects / requirements of generation types [62, 65, 101], have all served as core differences between differing power sources which must be considered along with carbon intensity. When comparing fossil fuel and VRE sourced power, for example, the dispatchability of the former and non-dispatchability of the latter, serves as a major distinction [43, 56, 61, 85, 86]. In a photovoltaic investigation for the USA, penetration (without compensation from storage, ramping dispatchables, *etc.*) was determined to face increasingly diminishing returns to expansion due to growing losses to curtailment [39]. The behavioural differences between VRE and fossil fuel energy types is therefore expected to result not only in different rates of carbon intensity, but also different characteristics in energy markets (these markets themselves also being of interest) [72].

Numerous studies have been performed to investigate these effects in a number of countries, in the context of VRE penetration (percentage of the generation mix), price, stability, and volatility [22, 68, 75, 77, 88]. Across these studies, VRE penetration and price are often uncorrelated or negatively correlated. A link between volatility the electricity spot price and growing VRE penetration levels is also identified. Sufficient compensation technologies are recommended to help prevent higher resulting energy prices [77].

Where VRE penetration has increased, the effects on the energy market and grid stability have been extensively investigated [42, 52, 53, 55, 60, 72, 102]. The extensiveness of German studies in this area present an interesting basis for comparisons with other countries, such as Britain, where less research has been conducted. Analysis of different markets within a country (such as the overall or imbalance markets) adds further detail in understanding this instability. It is therefore important to examine the effects of VRE deployment ongoing renewables developments, not only in the context of market-wide trends, but also in market subset data, such as marginal selling (price setting) behaviour in the imbalance market.

While decarbonisation policy has primary focused on the key differences in emissions intensity between VRE and fossil fuel energy, the structural issue of of inflexibility resulting from VRE non-dispatchability has been a topic of increasing interest [20, 67]. The issue of the emissions intensity of compensation technologies (such as gas) therefore arises. A

University of Victoria study, for example, found nuclear energy could be preferable source of green energy to VRE due to this dependency [94]. This phenomenon has been coined ‘The Renewable Energy Policy Paradox’ [9]. Analysis of the German market noted a ‘German Paradox’, where decreased (though still required) fossil fuel generation in the imbalance market supported the expanding contributions from non-dispatchables renewables in the overall market thanks to cross-market integration and improved forecasting [48, 72]. Consideration of the composition of the imbalance market is therefore critical in understanding both the economic and environmental challenges associated with the use of VRE generation and how they can be addressed.

The German energy imbalance market has been studied; both in its own right and by comparison (such as to the French market), with specific emphasis on the generation type of the marginal seller [46]. While there exist overall market studies for Britain and Germany, however, comparable literature investigating the British imbalance market is lacking. Due to the disproportionate price-setting role of the imbalance market, as well as the requirement to maintain the readiness (e.g. spinning reserves) of its potential contributors, a practical understanding of its behaviour in comparison to the imbalance market and its dependency on fossil fuelled energy is required.

This paper solves this problem by performing an extensive investigation into the British market, including its imbalance market. Context to existing literature is also critical. This is addressed by performing a comparative analysis of the overall British and German markets to identify individual and general behaviours in the British system. With this foundation a specific investigation into the British imbalance market is performed. The purpose of this paper is therefore to comparatively identify the trends of the energy transition in the British market, particularly with respect to the imbalance market.

2 Established Impacts of VRE Penetration

The effects of increasing VRE contributions to energy generation in British, German, and other markets has been of comparable academic interest. Compared to other generation infrastructure, differences in cost, dispatchability, and resulting compensation requirements, may be reflected market prices, volatility (of VRE volumes & prices), and the composition of the imbalance market (to which VRE is poorly suited to be a contributor). These phenomena are significant not only to the study of VRE’s direct effects, but also to the ability of the grid as a whole to respond to external stresses.

The consideration of literature in these areas should therefore be expanded upon to establish a benchmark of expectations (for calculations on Germany and Britain’s trends), determine the gaps in this knowledge (particularly the case in Britain), and create a reference point for potential counter-intuitive findings in the British imbalance market. Without imbalance adjustment from generation, storage, *etc.*, curtailment poses an increased limitation [39, 101]. In Britain, for example, it is calculated that although the mean average VRE penetration level is 23.21% (median 21.32%), the mean average level during a period of curtailment is 32.78% (median 32.94%).

A general trend may be found across many developed countries, where over the past decade, coal has been replaced by gas, wind, and solar in the generation mix [2, 15, 38, 82]. This transition has occurred in the UK and Germany, though the UK has comparatively displaced coal more thoroughly, while Germany has maintained a (domestically driven) dependency on lignite [3, 7, 15]. These British trends are reflected in data from the BMRS and DUKES databases (Appendix A.1) [12, 13, 30].

2.1 Price

The relationship between VRE penetration and energy prices have been extensively discussed over numerous timescales, with this paper comparing hourly/half-hourly penetration in specific due to its emphasis on imbalance compensation. The expansion of VRE generation and its effect on energy prices has been studied in numerous countries, with differing results. In the US a weak effect in lowering retail prices is identified [68]. In Japan, wind was found to have no significant effect in lowering prices, while solar did in some years [88]. A merit order effect motivated decrease in the spot price was identified in Colombia; demonstrating the ability of increased VRE generation levels to lower the electricity spot price, with a dependency on other technologies to meet imbalance / be the marginal seller [75]. In Germany prices have been noted to lower (though sometimes with VRE expansion only being a minor influence on price reduction), but with a dependency on VRE output forecasting [16, 32, 42, 55, 89]. The effects of other sources are also considered, such as gas, coal, and nuclear (the phasing out of which in Germany was noted to have had an upwards effect on prices) [47].

The impact of VRE penetration on price can thereby be seen to vary based on the country, timescale (especially long term effects), and generation type investigated. As this study will focus more on short-term impacts from factional penetration to the generation mix by VRE, and compensation from the imbalance market (for short-term requirements), a breakdown for Britain will therefore be performed using a half-hourly timescale. Due to competition, high VRE levels will be expected to coincide with lower energy prices while they occur. The longer term impacts of VRE dependency by the grid fall outside the scope of this investigation, with this study instead investigating trends such as the generation type of marginal seller (and its average price) in the British market at different levels of VRE penetration (expanding upon similar analysis in Germany [46]).

Methodologies for analysis in this area often include regression, and moving average approaches (of raw data and correlations) [71, 80, 98]. More specific approaches have also been developed in related forecasting studies [78–80]. Due to its ability to identify seasonal trends, the Seasonal Trend decomposition using LOESS (STL) trend (annual calibration) will be used in this paper; which uses local regression [50, 90].

2.2 Volatility

The potential relationship between price volatility (greater extremes, standard deviation, variance, *etc.*) and VRE penetration has been extensively investigated [5, 87]. These results are also investigated across differing countries and timescales. Higher volatility from VRE penetration was identified in Australia, the US (New England), and Europe (Spain, Germany, and broader markets) [4, 23, 63, 77, 81, 91].

Denmark (which like the UK has favourable conditions for offshore wind) was found to be a notable exception, where unlike in Germany (to which it was compared), the hourly price profile was flattened by the inclusion of wind power [81, 100]. "Access to flexible generation capacity" and "wind power generation patterns" were noted to contribute to this difference [81]. The weekly volatility of electricity prices, however, was found to increase in both Denmark and Germany, due to the intermittency of VRE generation. Across the studied markets, therefore, increased use of VRE was often associated with higher volatility of electricity prices, though with notable exceptions such as in Denmark on an hourly timescale.

2.3 Hydro / Storage

Storage technologies (hydro, batteries, hydrogen, ammonia, compressed air, *etc.*) have also been considered in conjunction with VRE sources such as wind, in the contexts of existing energy markets and variability compensation [6, 33, 51]. Of these, hydropower is heavily discussed, owing to its present scale of deployment (e.g. in Sweden, Germany, Turkey, and the Pacific Northwest [1, 47, 96]. These find hydro to assist in the integration of wind, though often as only a partial mitigation in its current scale. In a British estimation, if storage is to be responsible for meeting imbalances, then exponentially more will be required to compensate for the expansion of VRE infrastructure [57, 84].

2.4 Imbalance Market

The imbalance market is where supply-demand fluctuations from expectations/forecasts (such as those resulting from unexpected volatility, and its severity) are resolved to ensure grid stability [2, 72]). The bidding from this process, though subject to broader competition, ultimately determines the spot price of energy. Particularly where there are differences between the composition of the overall market and imbalance market, the disproportionate role of the imbalance market should be considered to ensure an understanding of price discovery [9, 46]. As they are non-dispatchable, VRE sources are particularly inadequate at fulfilling the needs of the imbalance market and are thus underrepresented. This lack of direct VRE feasibility in resolving supply-demand mismatches also makes the imbalance market of particular interest in the context of the energy transition [24]. Indirect merit order effect benefits [75] would still require complementary dispatchable energy to compensate for generation deficits.

Along with the earlier discussed solutions of hydro and other storage technologies (Section 2.3), gas generators (especially combined cycles gas turbines (CCGTs)) are also noted to perform a complementary role to intermittent renewables, and typically dominate the imbalance market, as may be expected [8]. The idea of 'The Renewable Energy Policy Paradox' was dubbed in an economic analysis the role of (dispatchable) fossil fuel generation in compensating for the inflexibility of VRE [9].

As such, expansion of the imbalance market to compensate for VRE sources may be generally expected, though this is not always the case. A 'German Paradox' was noted, for example, where increased efficiencies, and a more integrated imbalance market with the rest of Europe, led to Germany's imbalance market appearing to not require equivalent growth locally [36, 48, 72]). During year of 2020, for example, this dependency (particularly on France) was noted to be particularly acute [45].

Counter-intuitive, and anomalous results such as Denmark's lacking VRE effect on volatility (earlier discussed in Section 2.2), the 'German Paradox', and the increased renewables performance during 2020 are of critical importance to ensure a thorough understanding of real world phenomenon [45, 72, 81]. The 'paradoxically' expanding requirements for dispatchable capacity to offset the effects of the expansion of VRE has been documented both economically, and extensively in the German market (which this paper will hence use for comparison while performing an analysis more focused on the British market) [9, 46]. In these papers, fossil fuel energy is noted to be of increasing significance as the marginal (price-setting) seller of last resort [9, 72, 94]. In Germany, marginal selling from gas and hard-coal during periods of unmet residential loads increased, while low-marginal-cost / low-ramp-rate lignite and nuclear power were otherwise more common [46].

2.5 British & German VRE Penetration

While extensive literature makes German data promising for comparison, the British market will be of primary interest. VRE expansion has been a policy focus in both countries, which may be verified with respect to available data. Due to the overlap between VRE penetration levels, and compensation by marginal sellers (and the 'paradoxical' results therein), the British imbalance market will be of significant interest.

This paper will consider two years of German data, and five years of British data [10–13, 73]. These periods include significant VRE penetration levels in the overall markets of these countries. Figures 1 and 2, display the fractional VRE generation penetration in Britain and Germany (note the aforementioned difference timescales of data availability) along with the Seasonal Trend decomposition using LOESS (STL) trend (annual seasonality). The STL method will be discussed later, and will be used throughout this paper.

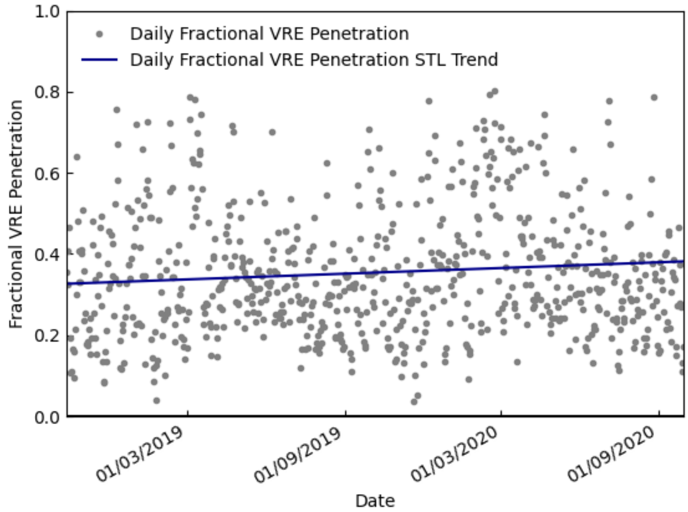


Figure 1: *Germany's fractional variable renewable energy (VRE) penetration (i.e. fractional generation). Daily fractional VRE penetration and trend (for readability). Points display the daily values, while the line shows the trend.*

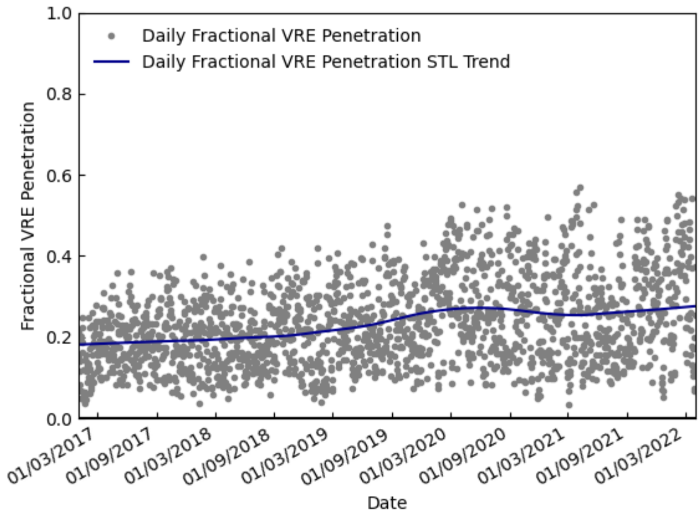


Figure 2: *Britain's fractional variable VRE penetration. Daily factional VRE penetration and trend (for readability). Points display the daily values, while the line shows the trend.*

The fractional VRE penetration in Figures 1 and 2 are both significant, and steadily growing. While there are similar objectives in the overall British and German renewable zeitgeists, significant differences between these systems may be observed, even at this level. For example, Germany saw higher levels of penetration, but lower levels of growth when compared to Britain (including within just the German data's timescale).

German and British data are therefore of both individual and comparative interest. As VRE continues to be expanded in Britain it will be important to determine the challenges faced by the electricity market. Increased market distress or diminishing environmental returns, such as those deriving from a reliance on / inability to displace fossil fuel generation (due to a need for non-intermittent generation) should be investigated thereafter by comparing the British overall and imbalance markets, expanding upon related methods employed in other countries.

3 Data & Methodology

This paper analyses data in three main areas:

- Overall German market (price, generation, type).
- Overall British market (price, generation, type).
- British imbalance market (price, generation, type).

Note that fractional (or percentage) penetration (i.e. of generation) will be discussed throughout this paper. This specifically refers to the contribution (of VRE, wind, solar, *etc.*) to the generation mix at each specific time (half-hourly, hourly, or daily window), as opposed to penetration over a longer timescale or some other metric such as installed capacity.

3.1 Overall German Market

Open Power System provides data on a number of countries [73]. Of these, Germany's data was most suitable for comparison to Britain. Generation (day-ahead) price, and type (for VRE: wind, solar, but not for other types) was available for Germany on an hourly timescale, from October 2018 to September 2020.

3.2 Overall British Market

By comparison, British data was on a half-hourly timescale for (spot) price, and type (for VRE: offshore wind, onshore wind, solar, and for non-VRE: coal, gas, nuclear, biomass, hydro, other). This information was taken from January 2017 to March 2022. The Balancing Mechanism Reporting Service (BMRS) was used as the primary source of information [10–14].

3.3 British Imbalance Market

BMRS data was also used as the main source of information on the imbalance market. Here, individual generation units are noted in the 'detailed system data', which can be mapped to a generation type either directly, or indirectly via an associated power-plant [11, 13, 14]. As types are not always provided, however, mapping to types listed the

Digest of UK Energy Statistics (DUKES) was also performed using Energy Identification Codes (EICs) and other details provided [30, 31, 69].

3.4 Data Decomposition

Various analyses on these datasets are performed (Section 4). For many of these analyses, results contain both trend components, along with significant seasonality. Observing the trend by removing seasonality is particularly significant given the high resolution of the data. This paper uses the Seasonal Trend decomposition using LOESS (STL) method (a common statistical approach for trend identification, de-noising, and prediction [19, 76]) to identify trends by removing noise and seasonality from an observed dataset.

Using the 'Statsmodels' Library in Python, STL decompositions were therefore performed (due to the suitability of this methodology to analyse datasets with these characteristics) [50, 90]. While the aforementioned high resolution of the data can make the visual identification of seasonality difficult, it is often significant enough to even be visible in the raw data. Regardless, while trends are generally discussed in the main paper, decomposition outputs can also be found in Appendix A.2. Graphed trends throughout this paper were thereby determined using the STL method.

4 Results and Analysis

Numerous examinations of German and British data are performed with respect to the trends of renewables in the energy markets. Given that more detailed data is available for Britain, more detail may be placed into its examination. Comparing both countries, however, is still of interest, with Germany serving as a benchmark while Britain is the primary focus.

4.1 Germany's (DE) Energy Mix & Overall Market

German (DE) energy data was obtained for the time-span of October 2018 to September 2020, on an hourly timescale. This data notes energy (day-ahead) price, energy demand, along with the output from solar, and wind. Compared to the data available for Britain (Section 4.2), this data, though not as comprehensive (in completeness, timescale, duration, and granularity), still allows for a number of comparable analyses to be performed; such as in Figures 1 and 2.

4.1.1 DE: Energy (Electricity) Demand

Firstly, to establish a background for the energy demand in Germany, the load is graphed in Figure 3.

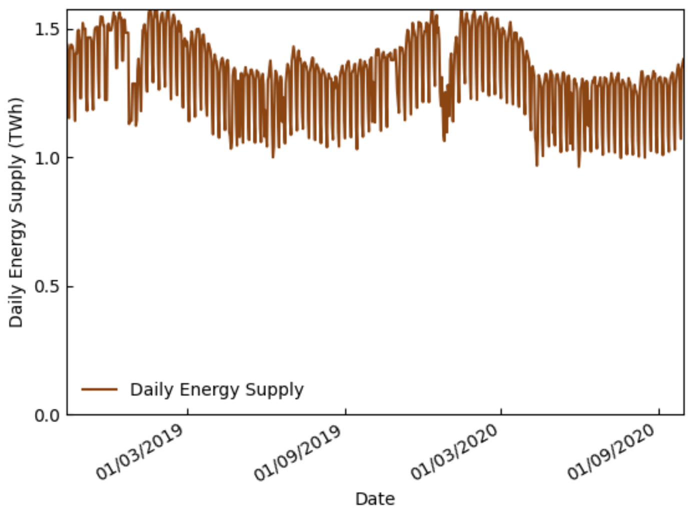


Figure 3: *Germany's daily energy (electricity) load (TWh).*

The observable seasonality in this data is to be expected given increased Winter (December (during the end of which is a load drop for the holiday break), January, February) demand. This annual seasonality should be kept in mind when considering further trends. Lesser weekly fluctuations also exist.

4.1.2 DE: Energy Prices and VRE Penetration

Previous studies generally find VRE penetration to be either uncorrelated, or negatively correlated with energy prices. How does Germany compare?

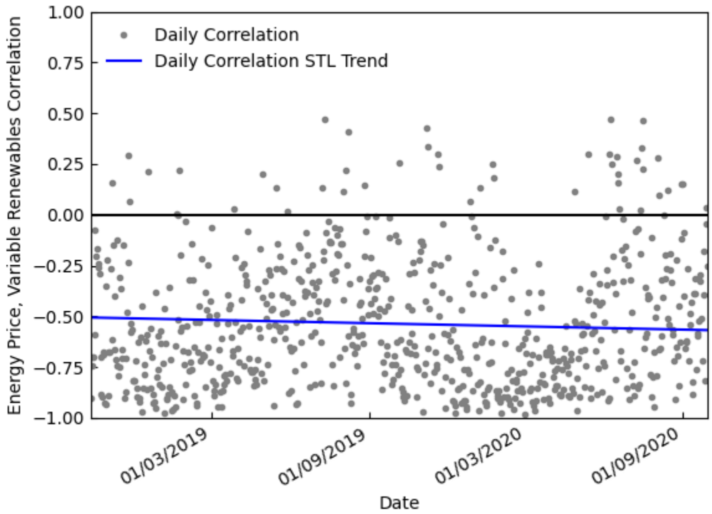


Figure 4: *Germany's energy price (EUR/MWh) to fractional variable renewable energy penetration correlation, and trend (for readability). This trend is persistently negative.*

As can be observed in Figure 4, a negative correlation coefficient trend exists between VRE penetration and energy prices. Seasonality is also observable in the raw data, with the higher-demand winter seeing the strongest negative correlation, though the (STL) trends are of primary interest in this analysis.

4.1.3 DE: VRE Penetration, and Energy Price Standard Deviation

Due to inflexibility from non-dispatchability, an increase in the standard deviation of VRE penetration is expected to occur alongside an expansion of penetration. Figure 5 notes this trend a daily basis.

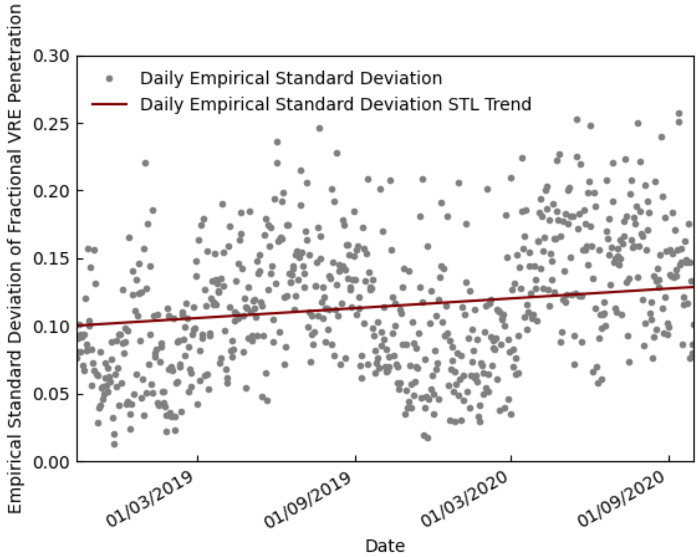


Figure 5: *Germany's standard deviation of fractional variable renewable energy penetration, and trend (for readability).*

Observable in Figure 5 is an increase in VRE penetration's standard deviation over time (as expected), though with significant seasonality. A more interesting trend exists in Figure 6, where the volatility of price does not show an equivalent increase.

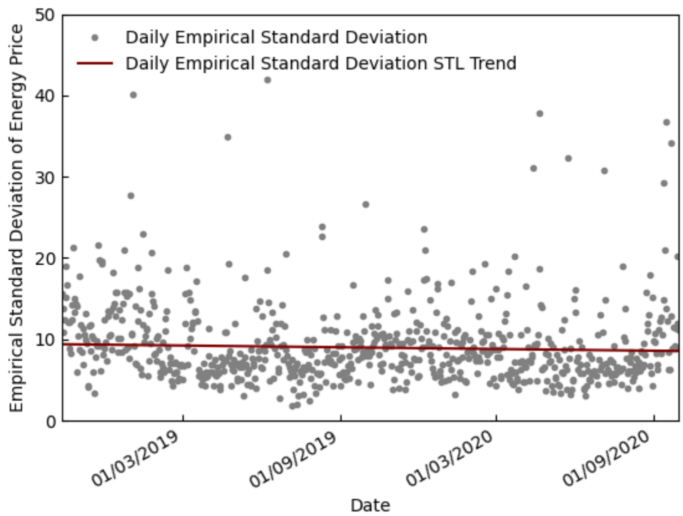


Figure 6: *Germany's standard deviation of energy price, and trend (for readability).*

4.1.4 DE: Energy Prices and Individual VRE Type Penetrations

The correlation between VRE penetration and price may also be broken down further into wind and solar separately, as seen in Figure 7.

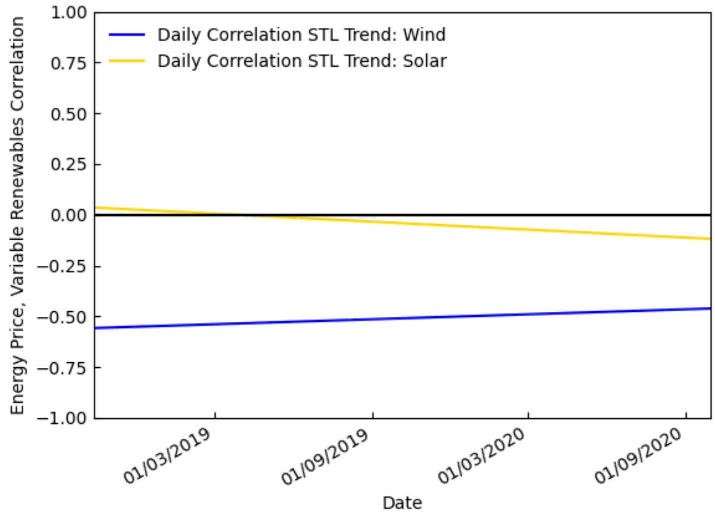


Figure 7: *Germany's energy price (EUR/MWh) to fractional wind, and solar (PV) penetration correlation. trends only (for readability).*

The negative correlation between VRE penetration and price is clearly driven by wind, with wind having a generally negative correlation while solar's correlation trends closer to zero. With approximately three times higher the average wind penetration compared to solar, this results in the overall trend observed in Figure 4. Note that penetration is in terms of fractional generation, not capacity (which is important, given solar's "dismal" [59, 66] capacity factor compared to wind in Germany).

4.2 Britain's (BR) Energy Mix & Overall Market

Data for Britain (BR) was comparatively more detailed than that obtained for Germany. While for Germany, the total (all sources) and renewables (wind (no onshore and offshore split) and solar) figures are provided, the British data differentiates by source (gas, oil, coal, wind (onshore and offshore), solar, biomass, other, *etc.*). Furthermore, British data is on a half-hourly timescale, over a longer timescale, and provides a spot price via its imbalance market (discussed later (Section 4.3 in detail). This allows for additional detail and figures to be provided to expand upon equivalent trends to those examined for Germany.

4.2.1 BR: Energy (Electricity) Demand

UK energy supply has been trending downwards (at least until 2020) for the past decade, with clear seasonality (higher demand in the UK's winter from December to February). Demand for the timescale this paper will examine is graphed in Figure 8.

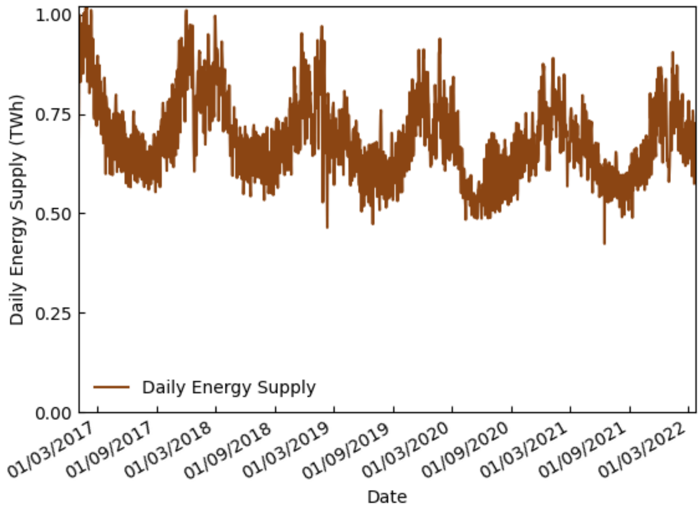


Figure 8: *Britain's daily energy (electricity) load (TWh).*

In Figure 8 similar trends to Germany are identified, including seasonality.

4.2.2 BR: Energy Prices and VRE Penetration

The correlation coefficient between the spot price and the summed generation of VRE sources is graphed in Figure 9.

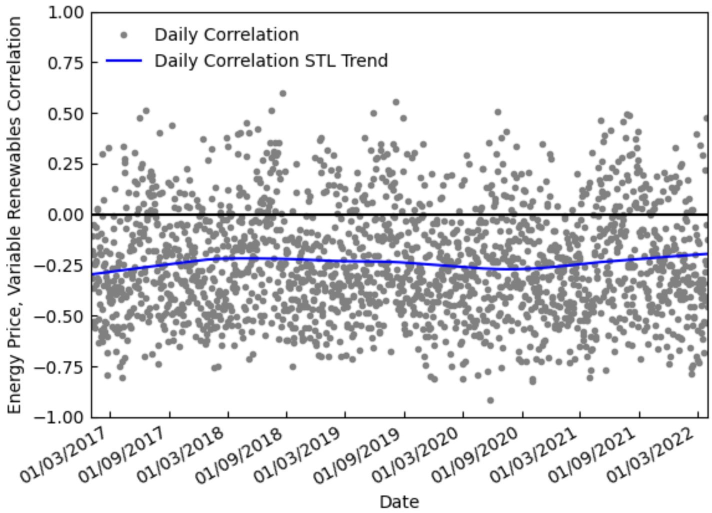


Figure 9: *Britain's energy price (GBP/MWh) to fractional variable renewable energy penetration correlation coefficient. Daily and trend (for readability). The trend is persistently negative.*

Figure 9 displays a generally weak, negative correlation between energy price and the proportion of energy contributed by VRE sources (though of a lower magnitude than in Germany).

Coal and gas can also be summed to devise a similar figure for the correlation between fossil fuel penetration and price.

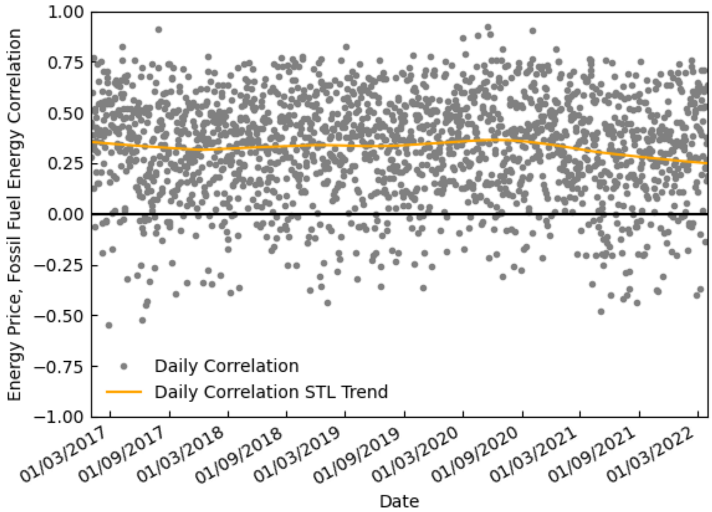


Figure 10: *Britain's energy price (GBP/MWh) to fractional fossil fuel energy penetration correlation. Daily and trend (for readability).*

In Figure 10, it can be seen that fossil fuels exhibit a generally weak, positive correlation with the spot price; a clear contrast to the VRE trend.

4.2.3 BR: VRE Penetration, and Energy Price Standard Deviation

As with the German data, the standard deviation of fractional VRE penetration is calculated, along with an associated trend.

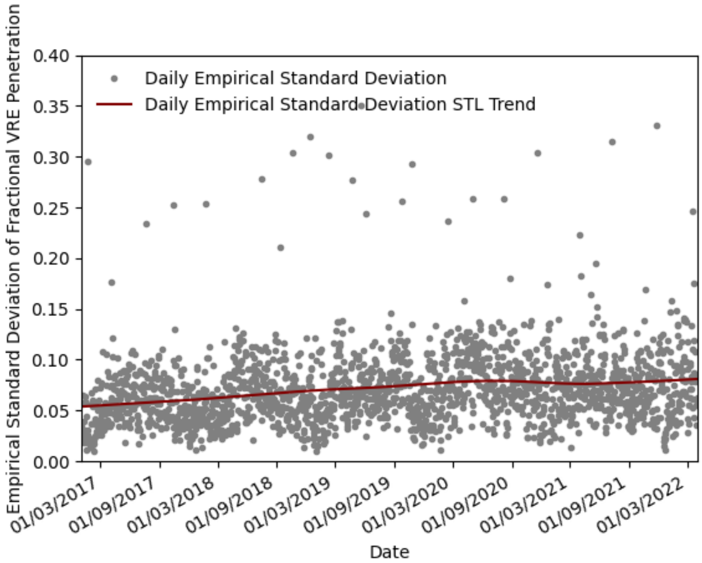


Figure 11: *Britain's standard deviation of fractional variable renewable energy penetration. Daily and trend (for readability).*

In Figure 11, the standard deviation can be seen to have increased steadily as expected. This corroborates the trends expected from an increasing VRE environment (particularly where storage, despite some growth, has not kept pace in resolving the variation of non-dispatchability; which is of particular relevance to the later discussed (Section 4.3) imbalance market).

The standard deviation, and trend, is also found for the energy price (GBP rather than EUR).

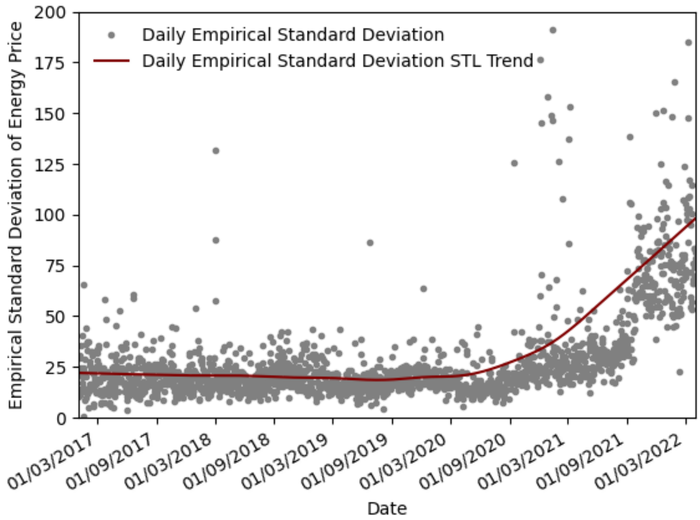


Figure 12: *Britain's standard deviation of the spot energy price, and trend. Due to a number of outlier prices, this image is cropped for readability, with the full version being shown in Figure 32.*

Figure 12 (which displays the standard deviation of the spot energy price) shows a more dramatic increase in recent years, before which it was constant. Thus, before 2020, British and German trends appear much more similar (with a significant difference in their price standard deviation trends since). Finally, while price volatility has increased since early 2020, the (slower) growth in VRE penetration volatility stalled in late 2020, though it remains historically high.

4.2.4 BR: Energy Prices and Individual VRE Type Penetrations

The comparison between energy prices and VRE penetration in Britain (Section 4.2.2) may be further decomposed by type. Here, the same analysis will be performed, but individually considering onshore wind, offshore wind, and (photovoltaic) solar. To avoid clutter, only the trends are graphed in Figure 13.

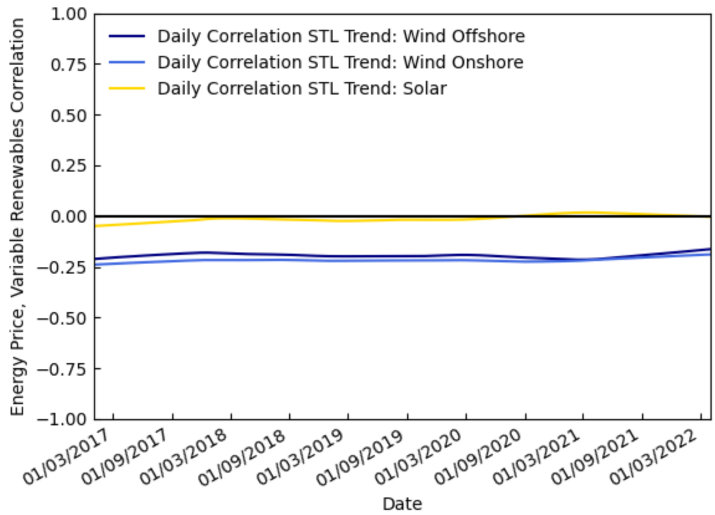


Figure 13: *Britain's energy price (GBP/MWh) to fractional offshore wind, onshore wind, and solar (PV) penetration correlation. trends only (for readability).*

A few key observations from Figure 13 may be noted. Firstly, both wind sources are clearly far more aligned with one another, than with solar. Secondly, wind power is also closely aligned with the overall VRE trend (Section 4.2.2) seen in Figure 9, which is unsurprising given their far greater contributions to the network. Thirdly, while wind has a persistently weak, negative correlation, solar's correlation is near zero.

4.3 Britain's Marginal Seller in the Imbalance Market

While the above cases focused primarily on the market's overall energy proportions, the marginal interactions on the imbalance market are of particular importance in influencing the market price (and the market as a whole by extension). Dispatchables were predictably responsible for over 99% of marginal sales (i.e. how often they were the marginal seller, as per data from the imbalance market). Using data from the energy market the generation type of the marginal seller was determined (for the majority of time instances). Of the known marginal sellers, four types were identified during the examined time period: gas at 89.66%, hydro (generally, or specifically re-pumped hydro) at 5.64%, coal at 4.18%, and wind at 0.53% (more detail in Appendix A.4). Hydro/storage is not only dispatchable, but also chargeable. If storage/hydro is excluded, then the imbalance market would have its marginal seller be gas overwhelmingly (95.02% of the time). The marginal seller type over time is shown in Figure 14.

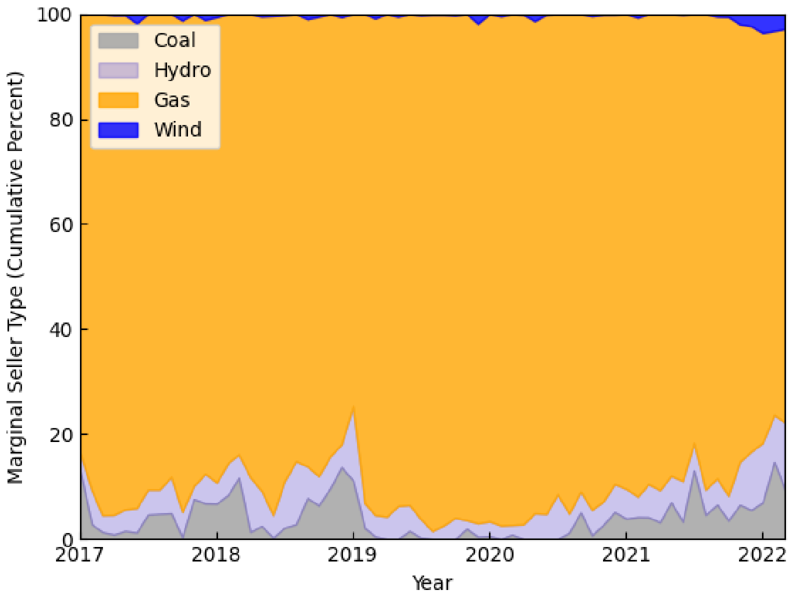


Figure 14: *Monthly Marginal Seller Type in the British Energy Imbalance Market (2017-2022). Ordered by average energy price (GBP/MWh) when each type is the marginal seller (-38.89 for wind, 67.42 for gas, 99.81 for hydro, and 102.02 for coal).*

The presence of wind (as negligible as it is), may be further broken down. Despite less than 2% (1.65%) of time periods having a $\leq$0 GBP/MWh energy price, the majority (87.85%) of the instances where wind is the marginal seller, occur when this is the case. Specifically, the average spot price when wind was the marginal seller was -38.89 GBP/MWh, as opposed to 67.42 GBP/MWh for gas, 99.81 GBP/MWh for hydro, and 102.02 GBP/MWh for coal. Wind power outside of the imbalance market, may still effect prices via competition, but its direct influence on the marginal side of the market, is certainly weaker. By extension, the displacement of gas (or even coal) by VRE, under existing trends, will be of increasing difficulty as dispatchability becomes increasingly important for remaining fossil fuel operators.

The most counter-intuitive finding, is the re-emergence of coal as a marginal seller in the energy (imbalance) market. While a broad range of factors may contribute to this paradoxical result, it should be further noted that this re-entrenchment has not been seen in the overall proportional generation rates in the energy market (Appendix A.1).

The re-entrenchment of coal from 2020 onward aligns with the price volatility increase in Figure 12 (unlike 2017-2019, which may also be of interest in future investigations of possible reversals). To further investigate this, a breakdown considering VRE penetration levels is performed. Figure 15 graphs the marginal seller type (in percentage terms) at different VRE penetration levels, along with also breaking down the percentage rate of each VRE penetration level (which for context has a mean level of 23.09%, and a median level of 21.30% for time periods with determined marginal seller types).

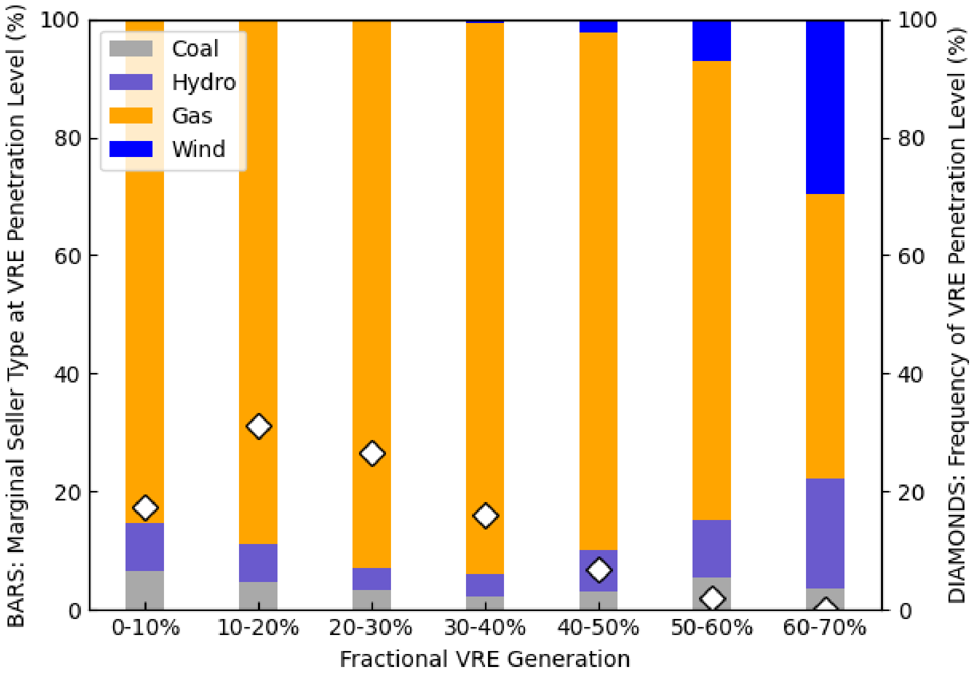


Figure 15: *Bars display the marginal seller generation type (as a percentage) during differing levels of VRE penetration. Diamond markers display the percentage of time periods during which this level of VRE penetration occurred. For example, while wind was the marginal seller 29.63% of the time when overall VRE penetration was at 60-70%, VRE penetration was rarely reached this level of contribution.*

In both Figure 14 and 15, gas clearly dominates. Furthermore, coal and hydro can be seen to be more responsible for grid compensation during periods of below average VRE penetration. As VRE penetration was negatively correlated with prices (Figure 9), this corroborates the higher average spot prices charged during periods of hydro and coal marginal selling (particularly evident for coal in Figure 15, as well as hydro when the frequencies of different VRE penetration levels are considered). The 'British Paradox', therefore appears to be most effectively explained by an increasing need for compensation (as indicated by volatility).

5 Discussion

Thus far this paper has reviewed the expected trends and counter-intuitive results in energy markets with respect to VRE penetration. Many of these trends were recreated and compared in Germany and Britain (the former being more extensively studied in past literature, and thus serving as an effective benchmark), though with recent developments of interest. In particular, a 'British Paradox' of coal reemergence in the imbalance market, coinciding with increasing volatility, was found.

Gas domination of the imbalance market is not unexpected. This aligns with past literature exploring (with notable exceptions) the paradoxically complementary nature of dispatchable fossil fuel generation in the imbalance market, and VRE expansion to replace fossil fuels in general market. In Britain's case, however, what was counter-intuitive was the resurgence of (previously declining) coal energy as the marginal seller in the imbalance market.

5.1 Underlying Trends in Britain and Germany

Firstly, the general trends can be summarised:

- In both Germany and Britain, periods of higher VRE penetration were correlated with lower energy prices. These correlations tended to be persistent, but weak, especially in Britain. This is calculated on an hourly / half-hourly time frequency and bares relevancy to cost-optimisation modelling (rather than long term price effects).
- These trends have resulted from the contributions from wind energy, rather than solar.
- In both Germany and Britain the volatility (standard deviation) of VRE penetration has steadily increased.
- The volatility (standard deviation) of energy prices, however, has remained constant in Germany and Britain until early 2020, after which in Britain (for which sourced data continues to a more recent date), a clear upwards trend is observed.

Annual seasonality was decomposed to more thoroughly investigate these trends.

It is not surprising that some anomalous results would be found in 2020, or since (in areas such as price volatility), however these changes are not uniform across markets. The paradoxical behaviour in the British imbalance market has not been matched by general generation trends (i.e. overall UK generation mix proportions do not reflect a resurgence in coal energy generation).

5.2 Effects in the British Imbalance Market: Coal Re-Entrenchment, Volatility

This coal re-entrenchment, is observed in the imbalance market, but not overall market. So while the overall market's coal penetration has declined, and policy guidance scenarios typically project a shift away from coal (capacity and generation), the use of coal as a marginal seller has increased. Based on these overall goals, coal contributions in the imbalance market may have been expected to be replaced by marginal sales from other sources such as gas or hydro, however, coal has instead re-emerged. Speculation as to the explanation of this 'British Paradox' should be careful to explain not only this phenomenon, but also its particular scope.

The imbalance market has been dominated (and still is) by gas generation. Coal, by comparison, has a higher average spot price when it is the marginal seller (i.e. marginal selling price). An alignment therefore exists between increasing price volatility (Figure 12) and increasing coal marginal selling (Figure 14), with coal (and hydro) serving as marginal sellers of last resort compared to gas (Figure 15). The imbalance market, therefore, seems to generally prefer gas to coal, with hydro (storage) interestingly serving a very similar function to coal (and having a similar average marginal selling price), as being more of an opportunist in the imbalance market.

The behaviour of the imbalance market is not necessarily in conflict with decarbonisation objectives, as can be seen in the changes in the overall generation mix, which the imbalance market compensates for. These results, however, do indicate that there is a significant difference between lowering energy generation from fossil fuels, and fossil fuel energy capacity. Under current imbalance market circumstances, fossil fuel (increasingly coal) capacity is used to compensate for the extremes in the overall market (even as its decarbonisation is pursued). This, however, is not exclusively the case for fossil fuels, as hydro (and potentially other storage by extension) appears capable of fulfilling a comparable role to coal (and thus competing with it).

Presently, however, the role of fossil fuels in the imbalance market remain persistently stubborn. Findings related to gas dominance in the imbalance market (despite a general emphasis on VRE expansion), therefore, are consistent with renewable energy (policy and market) paradoxes previously investigated [9, 46]. Coal re-entrenchment, however, is of particular note given the extent to which the trend of its contribution in the imbalance market has reversed while its decline remains clear in the overall market. The role of hydro (storage), while less counter-intuitive, was also shown to be of interest due to the similarity (pricing, VRE penetration compensation) of its behaviour to coal.

5.3 Future Role of Storage and the Imbalance Market

Most projected plans from the UK's government anticipate a phasing out of coal, while a continued role for gas remains present in some trajectories [25–29]. The resurgence of coal in the imbalance market, therefore, appears to be a matter of desperation. It may even be the case that there are observable limits in some 'efficiency vs stability' trade-off with respect to surplus capacity at the imbalance market's disposal.

Compared to these projections, the role of storage (to assist in compensating for increased VRE deployment) may have been underestimated [85, 86]. If coal replacement was pursued, then more gas and storage may be required (though new advancements in other compensatory technologies, such as rapidly practically ramping small-modular nuclear reactors could also be beneficial). Presently, however, storage may further assist the needs of the imbalance market. This may serve a specialised role in replacing coal, but with respect to future investigations more broadly, may also displace some marginal sales from gas generators.

Further investigations of market prices should also make particular note of the marginal seller's role in determining the spot price of energy. Future studies seeking to assess the decarbonisation role of storage operations, may seek to approximate this effect by examining the marginal seller type at that time (as opposed to the overall generation mix); which would overwhelmingly be gas. If storage were further sought as a marginal seller to displace coal (these being similarly priced), or gas, the negative VRE penetration to price correlation indicates that a profit motivated (cost optimisation) storage approach would be incentivised to displace fossil fuels in the imbalance market. This could complement VRE in the overall market, given that VRE generators lack the flexibility desirable in the imbalance market. The imbalance market is therefore of particular interest when investigating not only the spot price of energy, but also the environmental impacts of future expansions (such as in storage) given the first generation type to be displaced (from a techno-economic modelling perspective) would be that of the marginal seller.

5.4 Recommendations Summary

Under these conditions there is a disconnect between decreasing fossil fuel generation and capacity (the latter being disproportionately difficult to displace in the imbalance market, even if its application becomes increasingly that of compensation for VRE volatility). While this is consistent with past literature with respect to gas, coal's reemergence suggests a desperation in meeting the needs of the imbalance market (compared to national policy expectations). The market behaviour of hydro suggests storage can (where cost-viable) serve as a viable alternative in filling the market needs presently met by coal specifically, and gas more generally. Findings regarding VRE and market price trends suggest cost-optimising storage or demand scheduling (i.e. market based modelling) would complement VRE in the grid. Given the the imbalance market composition and pricing, however, competition with hydro storage may occur. Furthermore, estimations of storage decarbonisation may make use of the marginal seller's displacement (specifically, or generally gas) to contextualise their environmental impact.

6 Conclusion

This study comprised of two main components. Firstly, it confirmed many general energy market trends relating to VRE penetration, price, and volatility in Britain against the benchmark of Germany. Secondly, it further analysed these trends in the context of the British imbalance market and the marginal seller of energy (type).

- In Germany and, to a lesser extent, Britain, periods of high VRE penetration have a negative correlation with price. These trends:
  - Occur in a framework with annual seasonality;
  - Are specifically the result of wind energy contributions, and,
  - Are accompanied with higher VRE penetration volatility, and recently, considerably higher energy price volatility in Britain.
- The marginal seller in the British imbalance market is generally gas, though hydro and coal have regained their former (minority) proportions.
- The trend of coal re-entrenchment is counter to that of the overall market. This 'British Paradox' is in line with the aforementioned volatility increases, such that there now exist scenarios where coal regains cost viability (similar to hydro/storage).

As such, while higher VRE penetration is linked to lower energy prices (when it occurs), during periods of higher price (and generally lower VRE penetration) where compensation is required, higher volatility appears to facilitate a cost structure allowing the re-entrenchment of marginal sellers which typically sell at a higher cost (such as hydro, and coal, though gas remains dominant). Direct VRE penetration conclusions should therefore be tempered by these broader market effects (particularly with respect to this paper's recommendations).

Research Data

Raw data, such as that obtained from BMRS (for Britain) and Open Power System (for Germany) can be obtained using the references made within this paper. Code associated with this project may be found under version control at: https://github.com/cambridge-cares/TheWorldAvatar. A summary of the DUKES / BMRS mapping (used in conjunction with BMRS data) may be found in the following repository: doi:10.17863/CAM.92517.

Acknowledgements

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A Appendix

Here may be found additional information which is unnecessary for inclusion in the main paper, but may be of interest for additional detail.

A.1 UK Generation Mix Proportions

The proportional mix of the UK's energy generation is of interest, particularly with respect to noting the decline in coal (in the general market, which as the paper discusses, is interestingly not reflected in the imbalance market), and the growth of VRE. Two databases were used for this, DUKES (for which there are more years), and BMRS (the main source of data in this paper, and which at the time of writing has data published to a more recent date) [12, 13, 30].

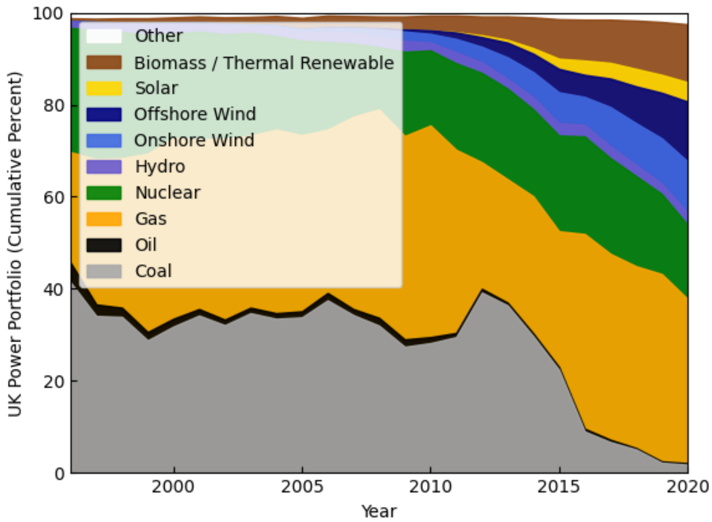

Figure 16: *DUKES: Proportional generation type of energy (electricity), in the UK.*

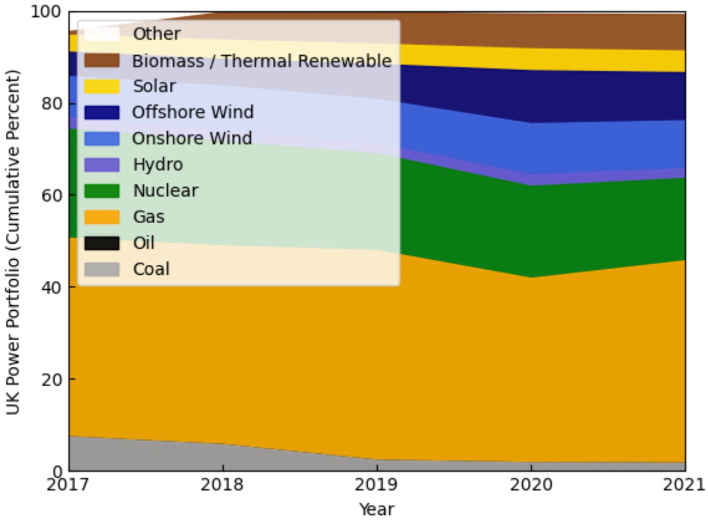

Figure 17: *BMRS: Proportional generation type of energy (electricity), in the UK.*

Note that in both these figures there is a clear trend of coal power decline and VRE growth, as advised to continue [29]. This is in contrast to imbalance market trends discussed through the paper.

Numerous sources also exist for Germany (and other countries), which may be of interest for future investigations into related topics [18, 41, 83, 93, 97].

A.2 STL Decompositions

Seasonal and trend decomposition using LOESS (STL) was performed to identify trends in various datasets analysed in this paper. This was performed for German and British data, which both considered multi-year periods. These were generated using the 'Statsmodels' Library for Python [90].

A.2.1 Decompositions for Introductory VRE Penetration

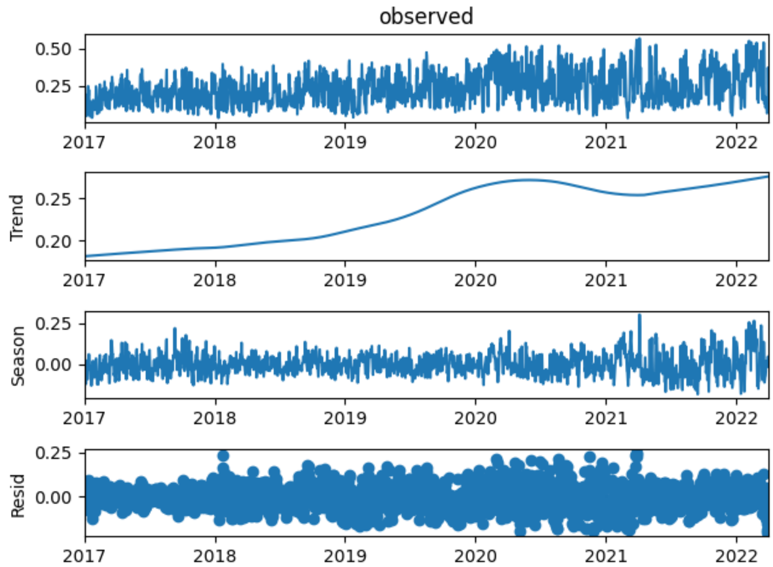

Figure 18: *STL decomposition of Britain's fractional variable VRE penetration. Corresponds to Figure 2.*

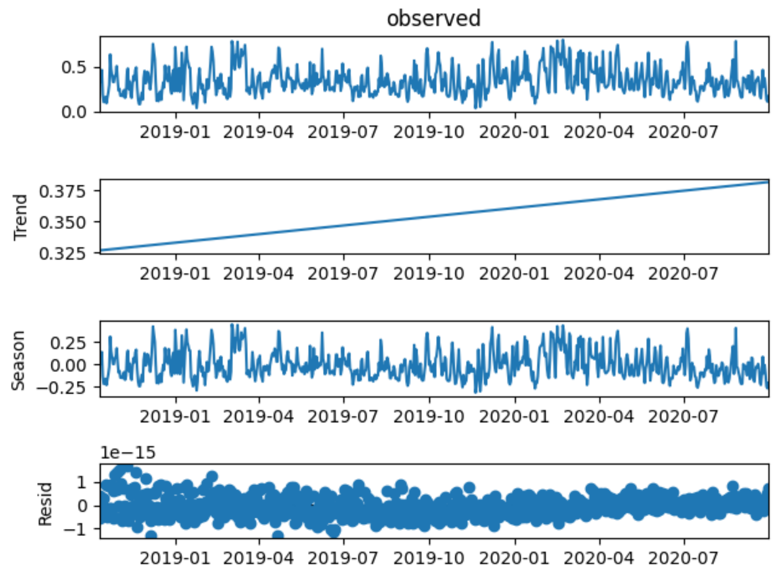

Figure 19: *STL decomposition of Germany's fractional variable renewable energy penetration. Corresponds to Figure 1.*

A.2.2 Decompositions for Energy Prices and VRE Penetration

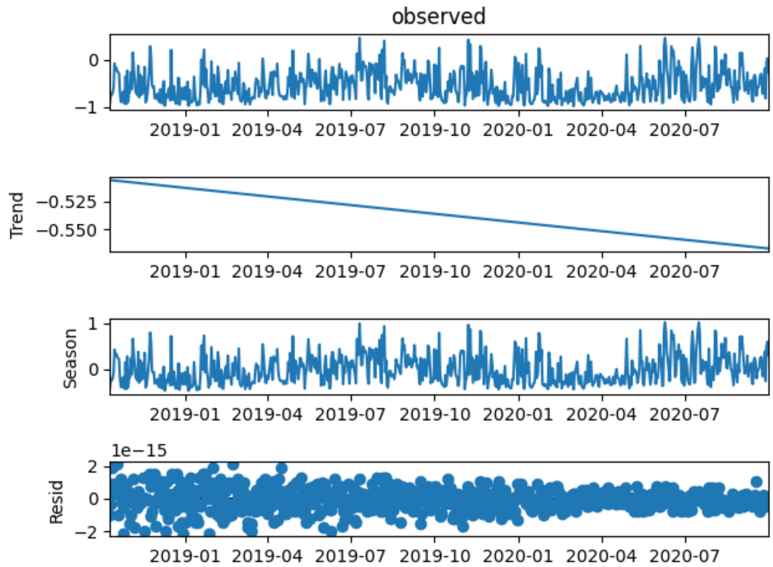

Figure 20: *STL decomposition of Germany's energy price (EUR/MWh) to fractional variable renewable energy penetration correlation. Corresponds to Figure 4.*

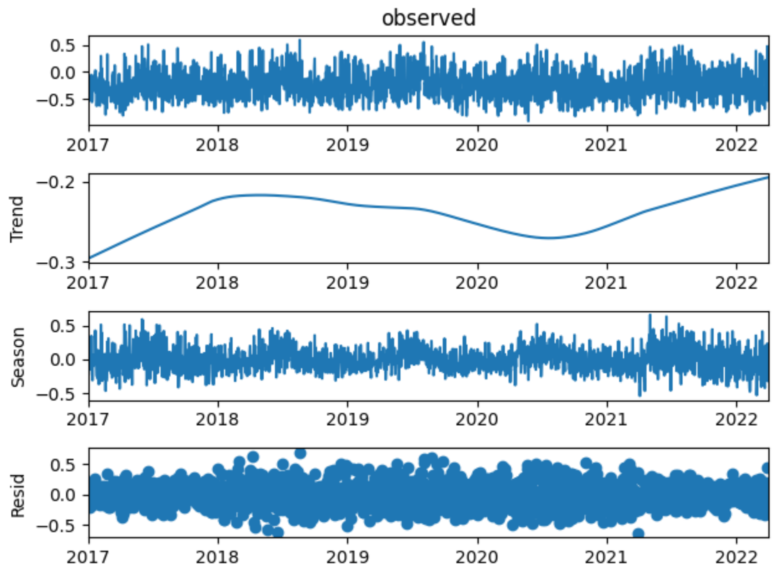

Figure 21: *STL decomposition of Britain's energy price (GBP/MWh) to fractional variable renewable energy penetration correlation. Corresponds to Figure 9.*

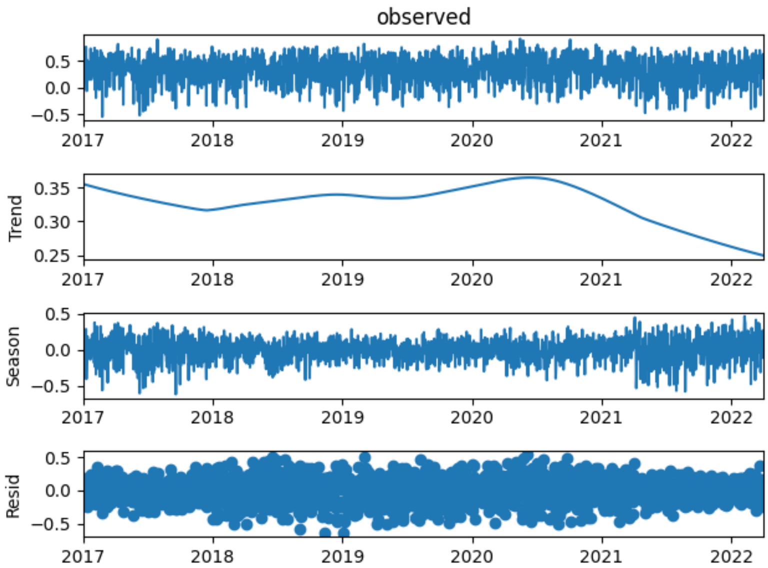

Figure 22: *STL decomposition of Britain's energy price (GBP/MWh) to fractional fossil fuel energy penetration correlation. Corresponds to Figure 10.*

A.2.3 Decompositions for VRE Penetration, and Energy Price Standard Deviation

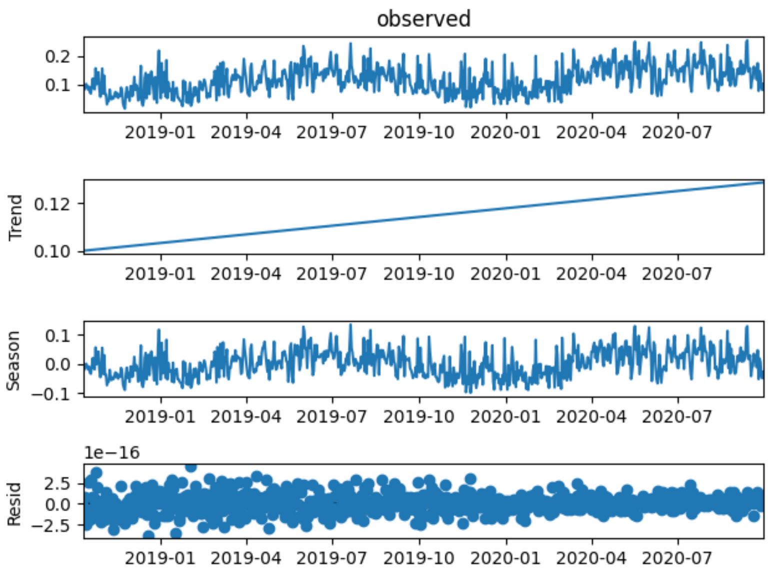

Figure 23: *STL decomposition of Germany's standard deviation of fractional variable renewable energy penetration. Corresponds to Figure 5.*

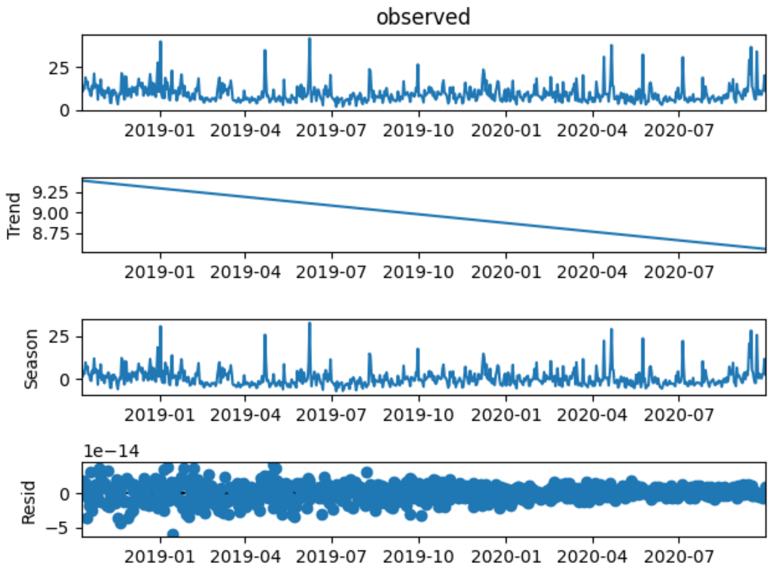

Figure 24: *STL decomposition of Germany's standard deviation of energy price. Corresponds to Figure 6.*

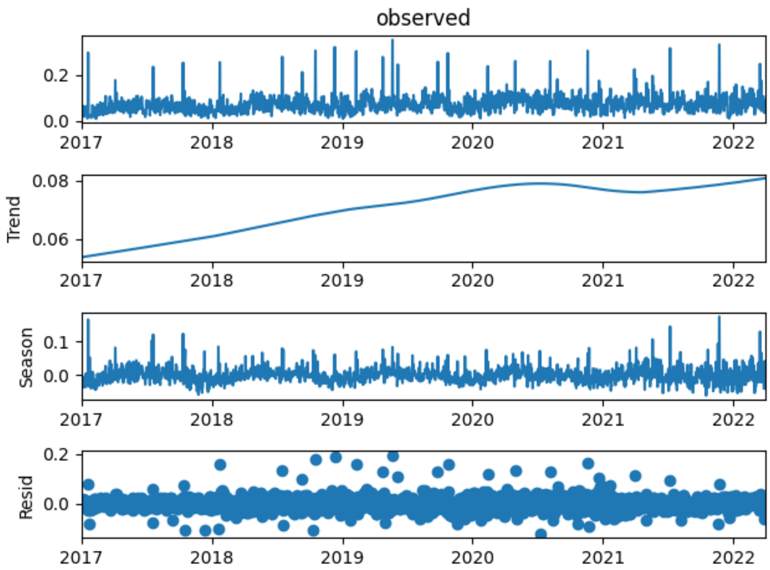

Figure 25: *STL decomposition of Britain's standard deviation of fractional variable renewable energy penetration. Corresponds to Figure 11.*

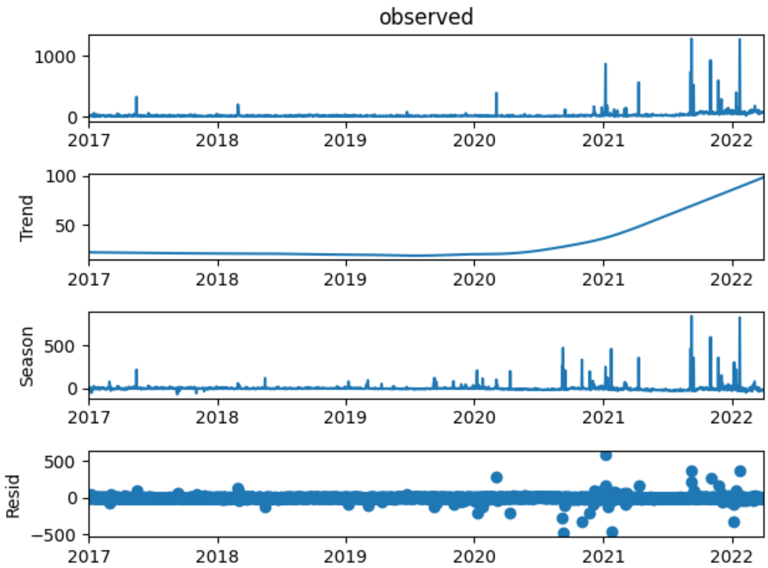

Figure 26: *STL decomposition of Britain's standard deviation of the spot energy price. Corresponds to Figures 12 and 32.*

A.2.4 Decompositions for Energy Prices and Individual VRE Type Penetrations

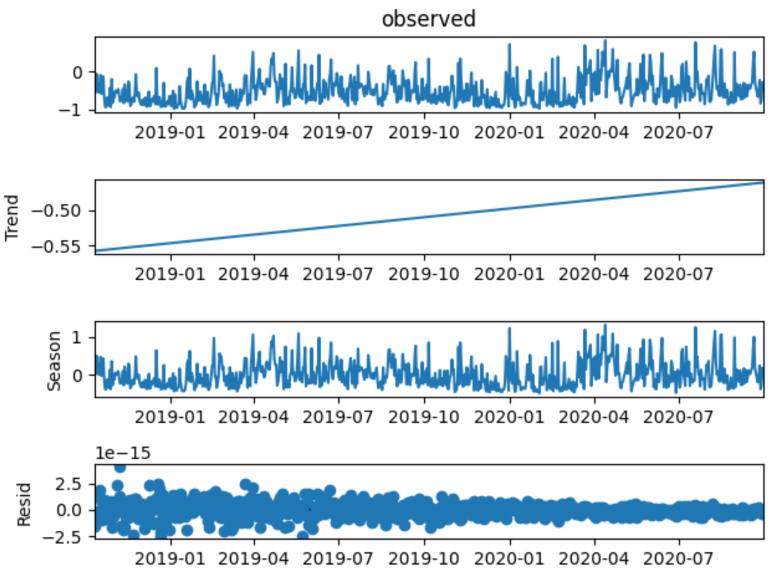

Figure 27: *STL decomposition of Germany's energy price (EUR/MWh) to fractional wind penetration correlation. Corresponds to Figures 7.*

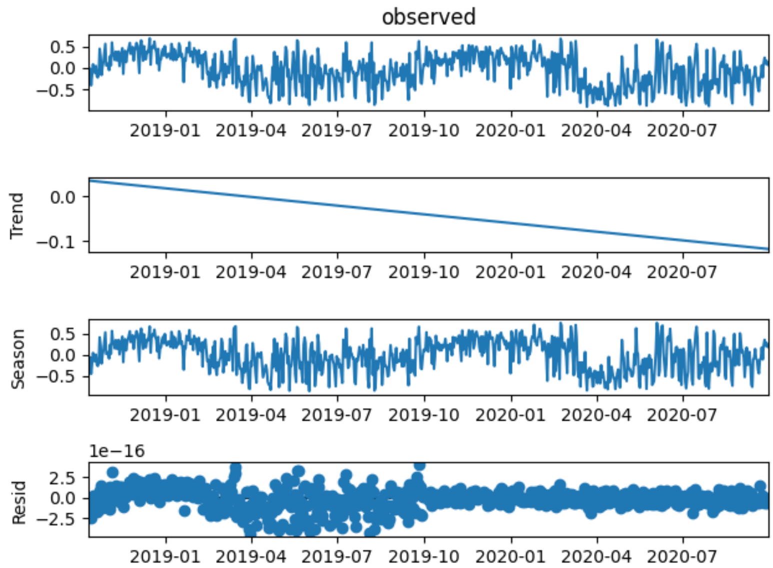

Figure 28: *STL decomposition of Germany's energy price (EUR/MWh) to fractional solar (PV) penetration correlation. Corresponds to Figures 7.*

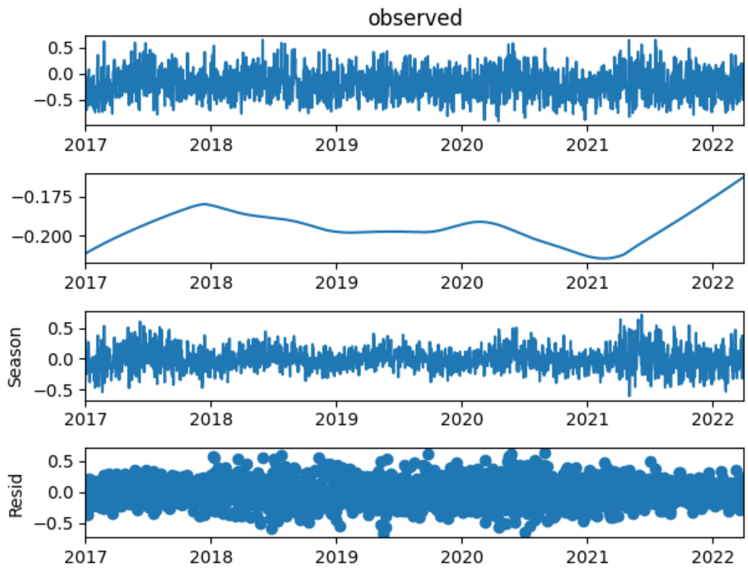

Figure 29: *STL decomposition of Britain's energy price (GBP/MWh) to fractional off-shore wind penetration correlation. Corresponds to Figures 13.*

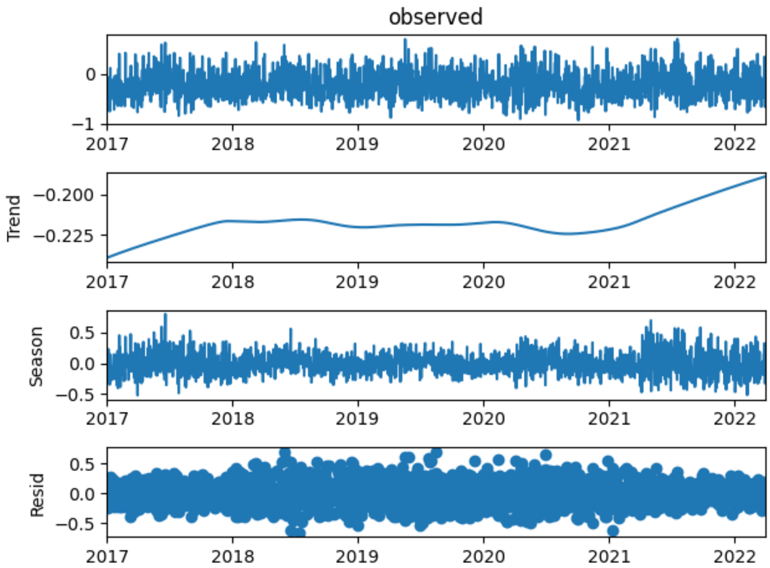

Figure 30: *STL decomposition of Britain's energy price (GBP/MWh) to fractional onshore wind penetration correlation. Corresponds to Figures 13.*

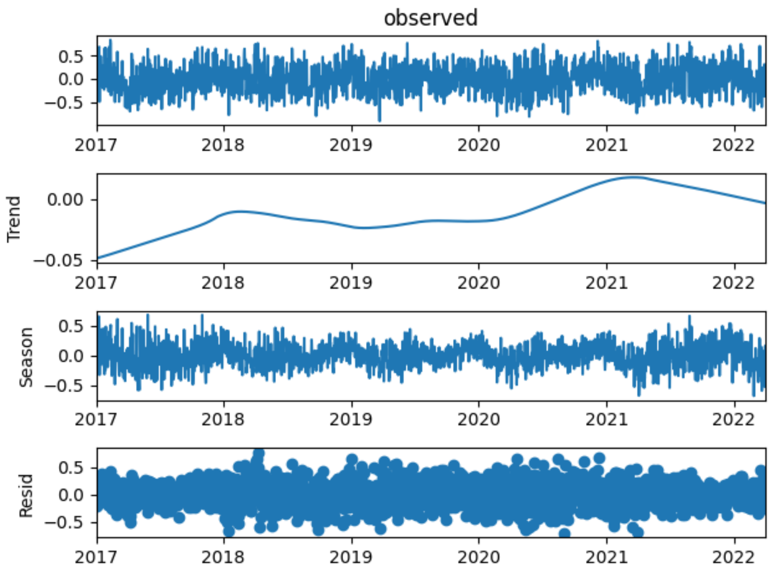

Figure 31: *STL decomposition of Britain's energy price (GBP/MWh) to fractional solar (PV) penetration correlation. Corresponds to Figures 13.*

A.3 Full British Energy Price Standard Deviation

Due to outlier points, Figure 12 is cropped for readability in the main document. Figure 32 shows the full version for completeness.

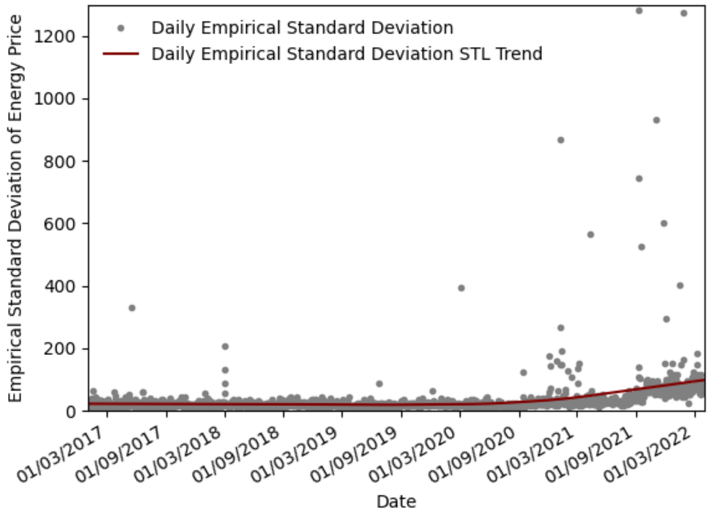

Figure 32: *Britain's standard deviation of the spot energy price, and STL trend. Due to a number of outlier prices, this image is cropped for readability, with the full version being shown in Figure 32*

A.4 Further Imbalance Market Details

The overall marginal seller type is overwhelmingly (overwhelmingly CCGT) gas (89.66%), but also contains hydro/storage (5.64%), coal (4.18%), and wind (0.52%).

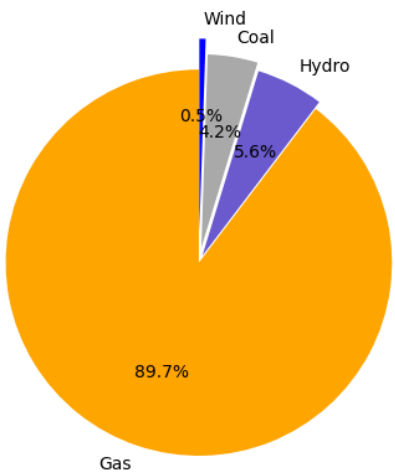

Figure 33: *Marginal Seller Type in the British Energy Imbalance Market (2017-2022).*

Figure 33 displays this breakdown. As might be expected under typical market operations, the vast majority of the time this role is fulfilled by gas (generally CCGT). Following this is hydro, which is either exclusively re-pumped, or with this capability; thus effectively serving a storage (or similar) role. Third is coal, which is similar to gas in being a dispatchable power source which may be used to meet imbalances. Finally, there is wind in a small fraction of cases. These wind cases are the most negligible, and are typically a reflection of ≤ 0 prices.

Returning to the more significant marginal seller types (gas, hydro, and coal), these sources fall clearly into the categories of typical dispatchables (gas and coal), and (also dispatchable) storage (hydro with re-pumping capability, or exclusively re-pumped). Thus, storage and fossil fuel dispatchables are the key competition on the marginal market, with these types' over-representation coming at the expense of VRE types compared to the overall market penetration of these types.

In the context of VRE, storage (such as re-pumped hydro) can play a uniquely complementary role, as it is not only dispatchable, but can further be charged using surplus renewable energy. If storage/hydro is excluded, gas to be the marginal seller type in 95.02% of mapped cases, as shown in Figure 34.

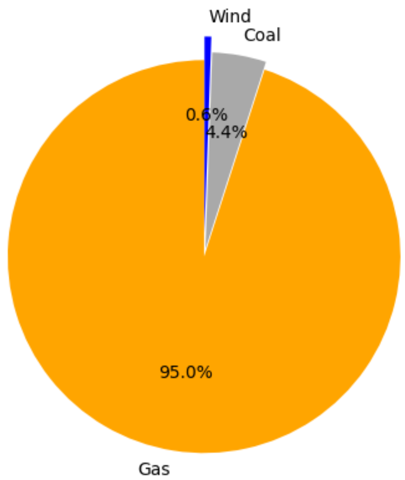

Figure 34: *Marginal Seller Type in the British Energy Imbalance Market, excluding storage/hydro (2017-2022).*

Due to the non-dispatchable nature of VREs, the marginal market is predictably still disproportionately dominated (compared to overall market penetration by type), by gas (and other dispatchables). While renewables penetration has grown, storage has been necessary to facilitate competition with fossil fuels on the imbalance market for the position of marginal seller. Given the significance of the marginal seller in the energy market (by having its sale determine the spot price), pure investigations of renewable expectations (particularly those considering marginal cost and associated price expectations independently of the bidding market) should be cognisant of this trend. Rather, by considering the disproportionate influence of the marginal component of the market (or by examining other methodologies (e.g. lifetime costs), more reasonable price expectations may be achieved.

This breakdown may also be considered on an annual basis (thus avoiding pervasive seasonal fluctuations determined earlier):

Table 1: *Marginal seller of energy on the imbalance market in Britain from 2017-2021.*

Year	Gas (%)	Coal (%)	Hydro (%)	Wind (%)
2017	90.94	4.15	4.54	0.37
2018	87.02	6.03	6.63	0.32
2019	93.34	1.61	4.71	0.34
2020	94.14	1.41	4.22	0.23
2021	87.85	5.37	6.23	0.55

Table 1 displays this breakdown. Due to the aforementioned seasonality, however, 2022 was not included (though out of interest it has currently has a breakdown of gas: 76%, coal: 10%, hydro: 11%, wind: 3%, but this would be better left to the monthly results in Figure 14). For the years where the full dataset exists, however, the most notable observation is the lack of a changing trend. While renewables have (particularly wind for the UK) grown in capacity and penetration terms, the direct effect in the price-setting margin appears to be non-existent. While the lack of a direct effect from wind is unsurprising, even if wind were to have an impact indirectly via storage, a clear trend in hydro is also not observed (though storage is a far more significant marginal seller than wind is directly). Seasonal and/or wind production forces may have been able to displace gas in the overall market (in penetration terms), but by comparison, the marginal market has not only been more stubborn, but exceptionally so.

Finally, some more details on pricing can be noted. This is performed to determine the average energy cost (GBP) by generation type (mean and median) in Table 2.

Table 2: *Average spot price of energy (GBP) for each marginal seller type.*

Average	Gas (GBP)	Coal (GBP)	Hydro (GBP)	Wind (GBP)
Mean	67.42	102.02	99.81	-38.89
Median	49.00	63.83	90.00	-63.72

The trends of higher coal and hydro prices, along with negative wind prices are consistent in both metrics of Table 2. The mean results are sufficient in discussing this trend in the main paper. Next, the average (mean) energy cost (GBP) at different levels of VRE penetration are shown in Table 3. Time periods where <30 instances occur (eg. if there are 0 instances) are listed as 'NA' (not applicable) due to statistical insignificance.

Table 3: *Average spot price of energy (GBP) at different VRE penetration levels, by year.*

Year	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
2017	52.10	47.02	40.19	32.09	24.09	*NA*	*NA*
2018	58.61	60.46	58.50	51.09	39.33	*NA*	*NA*
2019	51.34	45.14	41.09	35.95	27.98	12.01	*NA*
2020	49.98	41.4	35.25	33.43	24.47	17.23	*NA*
2021	134.26	125.33	109.56	106.45	94.93	68.56	*NA*
2022	312.81	235.32	211.30	196.72	159.85	126.91	54.00

The results of Table 3 are shown for completeness, but in the main document, Figures 9, 14, and 15 are sufficient in discussing pricing trends at different VRE penetration levels (and the fractional frequency of those VRE penetration levels). A clear trend exists where lower penetration levels result in higher prices. Notably, with respect to discussions of volatility, this trend persists when the VRE penetration level is below average (<20%), which has provided an opportunity for the re-entrenchment of coal in the imbalance market to compensate for low VRE penetration levels (when they occur).

While this imbalance market and its distressed use of coal has been primarily discussed with respect to price (Tables 2 and 3), the average proportional generation in the overall market may also be noted for each marginal seller type. The aggregate types in the overall market (as per the BMRS data [11, 12]) will be broken into Biomass, Hydro Pumped Storage, Hydro Run-of-River (ROR) and Poundage, Fossil Hard Coal, Fossil Gas, Fossil Oil, Nuclear, Other, Wind Onshore, Wind Offshore, and Solar. The marginal seller types, as elsewhere in this paper, are Gas, Coal, Hydro, and Wind.

Table 4: *Average percentage (%) composition of the general market for different marginal seller types (Gas, Coal, Hydro, Wind).*

	Gas	Coal	Hydro	Wind
Biomass (%)	5.94	5.58	5.75	5.90
Hydro Pumped Storage (%)	0.75	0.96	1.43	0.37
Hydro ROR and Poundage (%)	1.42	1.44	1.55	1.49
Fossil Hard Coal (%)	3.20	7.14	3.91	1.26
Fossil Gas (%)	43.24	46.11	45.07	20.27
Fossil Oil (%)	0.00	0.00	0.00	0.00
Nuclear (%)	21.77	18.55	20.28	25.76
Other (%)	1.34	1.11	1.15	0.85
Wind Onshore (%)	10.08	9.00	9.26	20.66
Wind Offshore (%)	8.03	6.74	7.84	18.06
Solar (%)	4.23	3.38	3.77	5.38

Table 4 makes this breakdown. While the imbalance market is significant in setting the market price, and has broader infrastructure cost implications (even if that infrastructure is often left in reserve), it is considerably smaller than the overall market in terms of energy volumes. Only minor differences in the overall market composition, therefore, may be expected between marginal seller types. Finally, while there are a variety of generation types shown, 'Fossil Gas (%)' will be primary focus when discussing the differences marginal seller types.

As was discussed earlier, wind tends to be the marginal seller during exceptional VRE output peaks. Rather than being deployed to account for unexpected demand, wind is often the marginal seller when excess generation drives down the market price, and thus other generators from the market. This is reflected in Table 4 by significantly lower gas output.

The higher 'Nuclear (%)' when wind is the marginal seller also implies these periods have relatively lower demand (as nuclear presently tends to produce a consistent power output, as opposed to gas, which is more commonly and easily ramped up/down). The reverse trend may also be seen for when hydro, and especially coal, are the marginal sellers. Table 5 verifies this by displaying the aggregated energy outputs themselves, including total generation (for mapped half-hourly periods).

Table 5: *Average aggregate generation (MWh) by type, of the general market, for different marginal seller types (Gas, Coal, Hydro, Wind).*

	Gas	Coal	Hydro	Wind
Biomass (MWh)	833.34	896.01	874.70	737.32
Hydro Pumped Storage (MWh)	121.48	174.84	241.72	54.66
Hydro ROR and Poundage (MWh)	210.70	244.94	244.66	186.40
Fossil Hard Coal (MWh)	543.23	1322.99	722.87	167.02
Fossil Gas (MWh)	6423.48	7929.54	7383.85	2673.70
Fossil Oil (MWh)	0.00	0.00	0.00	0.00
Nuclear (MWh)	3061.12	3022.96	3058.72	3140.83
Other (MWh)	198.19	190.11	183.47	107.32
Wind Onshore (MWh)	1456.10	1443.20	1345.18	2575.55
Wind Offshore (MWh)	1141.04	1057.31	1108.98	2226.94
Solar (MWh)	649.52	548.25	594.54	749.18
Total (MWh)	14638.19	16830.16	15758.68	12618.92

Figure 15 noted higher coal and hydro levels during particularly low VRE levels. If gas were used as a replacement in the overall market during these periods, and was thus less available to meet further imbalances, then a higher 'Fossil Gas (%)' may be expected when coal or hydro is the marginal seller in comparison to when gas is the marginal seller. This may be seen, though these differences are smaller than those observed when wind is the marginal seller. These results also align with the implications of the marginal sale price from Table 2. As such, these results appear consistent with earlier market analysis.

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